Charge States of Solar Cosmic Rays and Constraints on Acceleration Times and Coronal Transport

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ABSTRACT

We examine effects on the charge states of energetic ions associated with gradual solar flares due to shock heating and stripping at high ion velocities. Recent measurements of the mean charges of various elements after the flares of 1992 Oct 30 and 1992 Nov 2 allow one to place limits on the product of the electron density times the acceleration or coronal residence time. In particular, any residence in coronal loops must be for <0.03 s, which rules out models of coronal transport in loops, such as the bird cage model. The results do not contradict models of shock acceleration of energetic ions from coronal plasma at various solar longitudes.

Subject headings: acceleration of particles – Sun: corona – Sun: flares – Sun: particle emission

1. Introduction

Although particles from solar flares have been observed for 50 years (Forbush 1946), there are still many unresolved questions about their acceleration sites and mechanisms. Much recent research has focused on a simple classification scheme proposed by Pallavicini, Serio, & Vaiana (1977). In modern terminology, "impulsive" solar flares are typically defined as those with a short ($\lesssim$ 1 h) duration of X-ray emission, while "gradual" flares have a longer X-ray duration. These two classes of flares have been found to have several distinguishing characteristics. For example, X-ray emission from impulsive flares is observed to come from compact regions at low coronal heights ($\lesssim 10^4$ km), while X-rays from gradual flares tend to arise from broader regions or from large coronal loops up to $\sim 10^5$ km above the photosphere. In addition, it is widely believed that the main acceleration mechanism for particles escaping from impulsive flares is stochastic acceleration (second-order Fermi acceleration by gyroresonant plasma waves; e.g., Temerin & Roth 1992, Miller & Viñas 1993), while gradual flares are associated with shock acceleration higher in the corona (e.g., Cane, McGuire, & von Rosenvinge 1986, Lee & Ryan 1986), though not all observations support this paradigm (e.g., Mazur et al. 1992).

A more controversial issue is why solar cosmic rays are observed at locations that are magnetically connected to solar longitudes far from the longitude of the flare site. Because interplanetary diffusion is highly anisotropic, inhibiting motion perpendicular to the magnetic field (e.g., Palmer 1982), for decades it was assumed that particles are transported to other solar longitudes within the solar corona, whence they escape to travel along the interplanetary magnetic field to the observer. The seminal quantitative model of Reid (1964) assumes isotropic, two-dimensional, coronal diffusion, and gives specific predictions for the injection rate of particles into the interplanetary medium as a function of time and coronal distance from the flare site. It is not clear exactly what mechanisms give rise to coronal diffusion, though Newkirk & Wentzel (1978) presented the "bird cage" model of rigidity-independent coronal transport, in which flare-accelerated particles bounce back and forth inside coronal loops and occasionally transfer to other loops at the footpoints. On the other hand, it has recently been proposed that for gradual flares, with are often associated with large, interplanetary shocks, particles are freshly accelerated on open field lines at different heliolongitudes (Mason, Gloeckler, & Hovestadt 1984, Reames 1990). It is further assumed that coronal transport does not occur, and that for impulsive flares, which are usually not associated with interplanetary shocks, the narrower longitudinal dispersion (Reames, Cane, & von Rosenvinge 1990) is due to the spreading of magnetic field lines in the solar corona or the interplanetary medium. Therefore, it is no longer clear whether several decades worth of solar cosmic ray observations were providing information about the solar flare site, as previously assumed, or about acceleration at coronal or interplanetary shocks. Further progress in the interpretation of the information embodied in solar cosmic ray observations thus depends on the resolution of this issue.

Recent observations which can shed much light on this issue concern the charge state distributions of ions accelerated as a result of solar flares. Such distributions for various elements provide a rich source of information on the conditions of particle acceleration and escape from the corona. Results of the ULEZEQ instrument on board the *ISEE-3* spacecraft indicated that for several gradual flares, the charge states of 9 different elements were not consistent with the same temperature (Luhn et al. 1984), but rather had apparent ionization temperatures of 1 to 8×10^6 K. In contrast, summed results for several less powerful impulsive flares suggested that charge states of Si and Fe were characteristic of significantly hotter plasma, as might be expected if particle acceleration takes place at the site of a compact, impulsive flare (Luhn et al. 1987). More recently, measurements by three instruments on board the *SAMPEX* mission (Oetliker et al. 1995, Leske et al. 1995, Mason et al. 1995) have generally confirmed the earlier results for gradual flares, and also provide measurements for more elements, with better statistical accuracy, and for a broader energy range. A possible explanation for why the mean charges of energetic ions from gradual events are not consistent with a single temperature was given by Mullan and Waldron (1986), who proposed that photoionization by flare X-rays changes the ionization equilibrium in the plasma from which ions are accelerated, and obtained good quantitative agreement with the apparent ionization temperatures for various elements. Another possible explanation in terms of freeze-out temperatures was discussed by Mason et al. (1995).

In this report, we examine effects on the charge

states of energetic ions associated with gradual solar flares due two processes which would be expected to occur at the acceleration site. Although the physical conditions of the ion acceleration are poorly known, it is possible to roughly estimate these effects. If we accept that ions escaping after gradual flares arise from shock acceleration high in the corona, then one might expect significant electron heating, which is a general phenomenon of shocks in astrophysical plasmas (Schwarz et al. 1988). Another effect is that as the ions' velocity increases, their electrons are more likely to be stripped off (Hovestadt et al. 1984, Leske et al. 1995). We point out that if the ions spend a sufficiently long time at the acceleration site or in the solar corona, then these effects would influence the charge states in a manner that is inconsistent with the observations. This places limits on the acceleration time, and on the time spent in the solar corona after acceleration. These limits in turn rule out models of ion acceleration or coronal transport (such as the bird cage model) which require that escaping ions spend over ~ 0.03 s in a magnetic loop, while they do not contradict models in which ions promptly escape after acceleration on open field lines.

2. Effect of Shock Heating and Ion Velocities on Mean Charge States

As mentioned above, there are several recent reports of high-quality data on the mean charges of solar cosmic ray ions. Here we will mainly consider the results of Leske et al. (1995), who measured the mean charges of 12 elements with a high statistical accuracy at the relatively high energy of ∼15-70 MeV nucleon^{-1}. Very similar results were obtained for two large, gradual flares on 1992 Oct 30 (X-ray magnitude X1, importance 2B, at 22°S, 61°W) and 1992 Nov 2 (X9, 2B, at 23°S, 90°W; Solar-Geophysical Data 1993).

To place conservative limits on the acceleration or coronal residence time for solar cosmic rays, we assume that the charge states are originally characteristic of a relatively cool coronal plasma in thermal equilibrium, and that other effects, such as shock heating or increased stripping for faster ions, would tend to increase the charge. The lowest apparent ionization temperature that was accurately measured by Leske et al. (1995) is that for Si, $1.75\pm0.11\times10^6$ K, which was essentially the same on both 1992 Oct 30 and 1992 Nov 2. For a conservative limit, we use an upstream plasma temperature of $T_u = 1.5\times10^6$ K, which is also the average value obtained by Mullan & Waldron (1986) for their explanation in terms of X-ray photoionization.

The first effect which we consider is that of electron heating by shocks propagating through the corona, since it is widely believed that cosmic rays associated with gradual flares are accelerated by such shocks. Observations of a large number of fast-mode shock crossings of interplanetary shocks and bow shocks of Earth, Jupiter, and Uranus (Thomsen et al. 1987, Schwarz et al. 1988) imply that a fixed fraction of 0.12 ± 0.05 of the incident ion ram kinetic energy goes into electron heating, i.e., into increasing the electron enthalpy. From Figure 3 of Schwarz et al. (1988), we see that the jump in the electron temperature, ΔT_e, across the shocks in their sample is typically given by

$$\Delta T_e = (3 \text{ to } 9\text{K}) \times \frac{V_u^2 - V_d^2}{\text{km}^2\ \text{s}^{-2}}, \quad (1)$$

especially for $V_u^2 - V_d^2 > 2.5\times10^5$ km^2 s^{-2}, where V_u and V_d are the bulk flow speeds upstream and downstream, respectively, in the shock (de Hoffmann-Teller) frame.

To estimate the shock speed, we note that magnetohydrodynamic simulations indicate that the initial coronal mass ejection (CME) speed is roughly twice the average propagation speed of the forward shock to the Earth (Heras et al. 1995). Based on the K_p index of geomagnetic activity (U.S. National Geophysical Data Center, via World Wide Web), we estimate the initial CME speed for both flare events to be $V_u \approx 1500$ km s^{-1}. Assuming $V_d = V_u/4$ for a strong shock, the downstream electron temperature, T_d, is estimated to be 6 to 19×10^6 K. Note that since shock speeds determined from Type II radio bursts can be higher than initial CME speeds (e.g., Heras et al. 1995), using such speeds would yield higher downstream temperatures. A conservative limit on nt is obtained by considering $T_d = 7\times10^6$ K, which was also invoked in a mechanism proposed by Luhn et al. (1984) in which ions are suddenly heated to this temperature and the different apparent ionization temperatures for various elements are ascribed to different rates of approach to the new ionization equilibrium. For comparison, we also consider the effect of a higher value, $T_d = 1.5\times10^7$ K.

To calculate charge state distributions, we used the ionization and recombination rate coefficients of Shull

& Van Steenberg (1982), correcting the misprints in those tables reported in the errata (ApJS, 49, 351) and by Arnaud & Rothenflug (1985). The rate of change of n_q, the number density of ions of charge q, is given by

$$\frac{dn_q}{dt} = n_e[I_{q-1}n_{q-1} - (I_q + R_{q-1})n_q + R_q n_{q+1}], \quad (2)$$

where I_q and R_q are temperature-dependent rate coefficients (in cm^3 s^{-1}) of ionization from charge q to $q+1$ and recombination from $q+1$ to q, respectively. For ten elements, and different nt values, we used Euler's method to calculate the mean charges expected due to a) shock acceleration, in which particles are sometimes at T_u and sometimes at T_d (we used equal times for a conservative limit), and b) the mechanism of Luhn et al. (1984), in which ions are immersed completely in a new T_d. Table 1 shows the mean charges of various elements for case a). Note that for a higher T_d, smaller values of nt yield similar results. For case b), almost identical mean charges were obtained for nt values half as large. It is clear that neither mechanism is able to explain the observations. In particular, at $nt = 2 \times 10^{10}$ cm^{-3} s, the mean charges calculated for Si, S, Ar, Ca, and Ni were all above the 1σ limits of Leske et al. (1995), while those for O, Ne, and Fe were too low. We therefore place a conservative limit of $nt < 2 \times 10^{10}$ based on shock heating, where t is the total residence time at the shock.

Next we consider the effect of the ion velocity. The new observations of solar cosmic-ray charge states after gradual flares at higher energies, $\gtrsim 10$ MeV (Leske et al. 1995, Oetliker et al. 1995, Tylka et al. 1995), are in general agreement with those at lower energies (Luhn et al. 1984, Mason et al. 1995; note, however, that different mean charges are obtained for Fe, as discussed in the latter reference), which implies that little or no additional stripping occurs during the acceleration to higher energies or escape from the corona (Leske et al. 1995). Firstly, let us consider a limit on the integrated electron density times residence time in the corona after ions have been accelerated to their final energy, assuming that all changes in charge states relative to equilibrium at the plasma temperature occur during post-acceleration motion through the corona. Ions of 15 MeV nucleon^{-1} (at the lower end of the energy range measured by Leske et al. 1995) move at ≈ 6.4 times the rms thermal speed of electrons at our assumed plasma temperature of $T_u = 1.5 \times 10^6$ K. At these relative speeds, collisional ionization is far above threshold, and varies slowly with the relative speed, so we can neglect the effect of the thermal spread and approximate the ionization cross sections by assuming $v_{\rm rel} = v_{\rm ion}$. We use equation (2) to calculate the charge state distributions, but neglect the recombination rates because the charge states characteristic of T_u are far from the equilibrium for such a high velocity. For ionization rates, we employ the energy-dependent ionization cross sections σ_q of Arnaud and Rothenflug (1985), and set $I_q = \sigma_q v_{\rm rel}$. Again, the charge state observations for various elements cannot be explained for any value of nt. As for the case of shock heating, the tightest limits on nt are obtained for Ar, Ca, S, and Si. The nt values for which the calculated mean charges exceed the observed mean charges by one standard deviation are shown in the third column of Table 2. From these we conclude that nt should not exceed about 3×10^9 cm^{-3} s during transport through the corona.

Similarly, if we assume that all deviations from thermal-equilibrium charge states occur during acceleration, we can derive limits on the acceleration time. Here we need to consider the changing velocity of the ion. In fact, for slower ions the rate of ionization is faster, though the ultimate equilibrium charges would be lower. To be conservative, we only consider the final e-folding in momentum from 61 to 167 MeV c^{-1}, corresponding to kinetic energies from 2 to 15 MeV, and assume as a rough approximation that the rate of change of $\log(p)$ is constant (which requires that the spatial diffusion coefficient should be roughly constant over that energy range). The resulting nt values for which calculated mean charges exceed the observed mean charges by one standard deviation are shown in the second column of Table 2, where t represents the momentum e-folding time. We can conclude that the maximum momentum e-folding time during acceleration, which is commonly called the acceleration time, is given by $nt < 2 \times 10^9$ cm^{-3} s. Since the limits we derive for acceleration and coronal residence times are of a similar magnitude, we can alternatively say that $nt < 3 \times 10^9$ cm^{-3}, where t is the acceleration time plus the residence time in the corona. The earlier limit derived from the effect of shock heating is less stringent than that from the effect of the ion velocity, so we will use the latter in the following discussion.

3. Discussion

We have implicitly made the standard assumption that the charge states of solar cosmic rays are fixed in the corona and unaffected by interplanetary transport. This is justified by considering the above limits. Given that solar wind densities are on the order of 4-12 cm^{-3} (Foukal 1990) near Earth, and vary as the inverse square of the radius from the Sun, ions could travel for years throughout the inner solar system without being substantially stripped. However, for the much higher densities within the solar corona, these limits on nt correspond to much shorter times.

A related point is that Tylka et al. (1995) have stressed that most measurements of the mean charge of iron are incompatible with acceleration directly from the ambient solar wind (Reames 1990). This point is supported by previous theoretical and observational studies (e.g., Terasawa & Scholer 1989, Tan et al. 1990), which found that at energies $\gtrsim 1$ MeV, interplanetary shocks only re-accelerate an existing population of somewhat lower energy. The observed charge states seem to require an initial acceleration from coronal material. This does not rule out the possibility that a CME-driven shock accelerates particles while inside the corona, or perhaps near the Sun (Kahler, Reames, & Sheeley 1990) while pushing coronal material in front of it (Boberg, Tylka, & Adams 1996).

We consider the implications of limits on the product of the electron density and the time of acceleration or residence in the corona for models of coronal transport. While the flare of 1992 Oct 30 was at a solar longitude of 61° W that could be magnetically well-connected to the detectors near the Earth, the flare of 1992 Nov 2 was at $\approx 90°$ W, so the hypothesis of coronal transport would have to account for a net displacement of about 4×10^5 km. If we consider the limit of $nt < 3 \times 10^9\ \mathrm{cm}^{-3}$ s in the corona after and during acceleration, the electron densities in various regions of the corona (and the corresponding limits on t) are roughly $10^{11-12}\ \mathrm{cm}^{-3}$ (0.003-0.03 s) in coronal loops, and $5 \times 10^7\ \mathrm{cm}^{-3}$ (60 s) at a height of 10^5 km in the quiet Sun (Foukal 1990). As field lines outside the loops rapidly open up with height, the density rapidly decreases, until $n \sim 10^5\ \mathrm{cm}^{-3}$ ($t \lesssim 3 \times 10^4$ s) at $r = 2R_\odot$.

These limits essentially rule out the "bird cage" model of rigidity-independent coronal transport (Newkirk & Wentzel 1978) for escaping ions from these gradual flares. In this model, particles are stored inside coronal loops, mirroring back and forth between the footpoints and occasionally transferring to a different loop. However, the above limits show that the ions which escape could have traveled at most 1.6×10^3 km inside a coronal loop, which would only be a small fraction of the loop's length, and is far shorter than the coronal distance from the site of the 1992 Nov 2 flare to the footpoint of the detectors' magnetic field lines. Thus if the ions which are observed are accelerated inside a loop, the acceleration time must be very fast (< 0.02 s), and the ions must escape immediately and cannot be transported along the loop.

If a mechanism for coronal transport does not involve the motion of ions in coronal loops, e.g., by transport along current sheets (Fisk & Schatten 1972; note that such transport would be rigidity-dependent), the above limit on the time spent at a coronal height of $\sim 10^5$ km allows a 15 MeV $\mathrm{nucleon}^{-1}$ ion to travel about 3×10^6 km. However, the above limits on nt are very conservative, in that they permit an ion's mean charge to change from the value characteristic of 1.5×10^6 K to the measured values, while in fact there seems to be little change in the mean charges of observations spanning two orders of magnitude in energy. It is possible that *SAMPEX* observations could yield $d\langle Q\rangle/dE$ for a single instrument, placing more severe constraints on nt and on coronal transport models in general (see also Oetliker et al. 1997).

Our results favor models in which the acceleration of ions observed after gradual flares takes place on open magnetic field lines (e.g., Lee & Ryan 1986), and in which the longitudinal distribution of solar cosmic rays from such events is due to acceleration distributed over a range of heliolongitudes.

Since the effects of shock heating and ion velocities cannot explain the different apparent ionization temperatures for various elements, the best quantitative explanation is that of Mullan and Waldron (1986). An requirement of this model is that similar X-ray fluxes must be present at the acceleration site for all of the observed flares, over a time sufficient for ionization equilibrium to be established, before a shock arrives and accelerates the ions. Note that the X-ray flux should decrease with increasing coronal distance, and be eclipsed for low heights at large coronal distances. If one believes that observed ions are accelerated near the footpoint of the observer's field line,

then the fact that there is no apparent dependence of the mean charges on the coronal distance (e.g., for the flares of 1992 Oct 30 and 1992 Nov 2) may be problematic for either the distributed acceleration model or the photoionization model.

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TABLE 1

Mean Charges due to Shock Heating[a]

			$T_d = 7 \times 10^6$ K		$T_d = 1.5 \times 10^7$ K	
Element	Measured[b]	$T_d = T_u$	$nt = 1 \times 10^{10}$	$nt = 2 \times 10^{10}$	$nt = 5 \times 10^9$	$nt = 1 \times 10^{10}$
N	6.47±0.20	5.82	6.09	6.28	6.12	6.33
O	6.95±0.20	6.20	6.42	6.60	6.48	6.71
Ne	8.53±0.27	7.99	8.05	8.10	8.10	8.19
Mg	10.30±0.34	9.89	9.96	9.99	9.98	10.03
Si	10.54±0.37	9.65	10.65	*11.14*	10.64	*11.15*
S	10.84±0.44	9.19	10.71	*11.42*	10.76	*11.57*
Ar	10.08±0.91	9.54	*11.02*	*11.81*	*11.13*	*12.05*
Ca	11.46±0.49	10.35	11.48	*12.18*	11.66	*12.52*
Fe	15.18±0.73	10.39	12.68	13.09	12.64	13.19
Ni	12.62±1.30	9.32	12.70	13.76	12.52	13.92

Note.—Units of nt are cm^{-3} s.

[a]Calculated assuming that ions spend equal times at $T_u = 1.5 \times 10^6$ K and at T_d. Italicized values are those
in excess of the measured values plus one standard deviation.

[b]Leske et al. 1995.

TABLE 2

Limits on nt for Fast Ions

Element	nt during acceleration, 2 to 15 MeV nucleon^{-1}[a] (10^9 cm^{-3} s)	nt after acceleration, 15 MeV nucleon^{-1} (10^9 cm^{-3} s)
Si	2.6	4.8
S	2.3	4.4
Ar	1.2	2.2
Ca	1.6	2.6

[a]Over a factor of e in momentum, i.e., from 61 to 167 MeV c^{-1} nucleon^{-1}.